L.4: Growth of monocrystalline DBR mirrors with reflectivity exceeding 99% and high Q resonator

"Monocrystalline reflectors", as end mirrors in a Fabry-Parot cavity, are the state of art design for achieving extremely high reflectivity at the desired wavelength range. Additionally, a monocrystalline semiconductor structure consisting of a quantum well, between the two high reflecting distributed Bragg-reflector (DBR) mirrors offers rich fundamental science in the field of strong light matter coupling, which led to various novel phenomena. This includes detection of single photon/spin in quantum dots, Bose-Einstein condensation in solid, observation of exciton/polariton mediated super-fluidity and the formation of quantized vortices. These structures remain the backbone of vertical cavity surface emitting lasers and are being used for developing compact and efficient terahertz sources. Recently, ultra-stable, low elastic loss monocrystalline mirrors based on GaAs/AlAs and GaAs/AlGaAs DBR have also been proposed for laser interferometry based gravitational wave detection and large-area ring laser gyroscope.

GaAs/AlAs hetero-structure remains an ideal (gold standard) system for above work because of mature growth technology, minimum strain between the layers and reasonable contrast in the refractive indices. In view of above, quarter-wave ($\lambda/4n_{eff}$) thick alternating high and low index of GaAs/AlAs, GaAs/AlGaAs based structures with reflectivity higher than 99% at technologically important wavelengths such as 808, 880, 1064, 1150 and 1550 nm are designed. The designed monocrystalline DBR structures consist of typically 20 to 30 pairs of GaAs/AlAs or GaAs/AlGaAs crystalline multilayers that are optimized based on the theoretical value of desired reflectance for the specified wavelength range (Figure L.4.1(a)). The theoretical reflectance calculation is based on the complex-matrix formalism of the Fresnel equations. Similarly, the DBR mirrors are used to form the micro-cavity resonator by sandwiching a $3\lambda/2n_{eff}$ $Al_{0.22}Ga_{0.78}As$ layer between two such mirrors (Figure L.4.1(b)). The front and back cavity mirrors are composed of 14 and 20 bilayers of $Al_{0.22}Ga_{0.78}As/AlAs$, respectively. The designed DBR mirror and resonator structures are grown on GaAs substrates by using metal organic vapour phase epitaxy (MOVPE). Photograph of DBR mirrors of 2-inch diameter are shown in Figure L.4.1(a) and the inset shows the reflectivity spectrum of 1550 nm DBR mirror. 100 nm wide stopbands and sideband oscillations on either side of the stop bands confirm the excellent quality of the grown mirrors. In the resonator structure, the asymmetrical design of DBR layers enables light to be injected into and emitted from the same side of the cavity. In order to enhance the coupling strength, a quantum well (either GaAs or InGaAs) is also embedded inside the micro-cavity. At room temperature, well defined cavity resonances (at λ_{res}) are observed with FWHM < 1 nm leading to Q-factor in excess of 1000 (Figure L.4.1(c)). To investigate the strength of coupling, between the quantum well exciton and the micro-cavity, the λ_{res} has to be tuned around the quantum well transition energy (λ_{ex}), which was made possible by tuning of temperature and angle of incidence. Variation of temperature from 10 to 300 K results in nearly 12 nm shift in λ_{res}, though in the same range, λ_{ex} shifts by approximately 52 nm. On the other hand, change in incidence angle from normal incidence to 70° resulted in 33 nm shift in λ_{res}, without any change in λ_{ex} (Figure L.4.1(d)). Such difference in relative variations offers the flexibility to tune the coupling strength in the same structure.

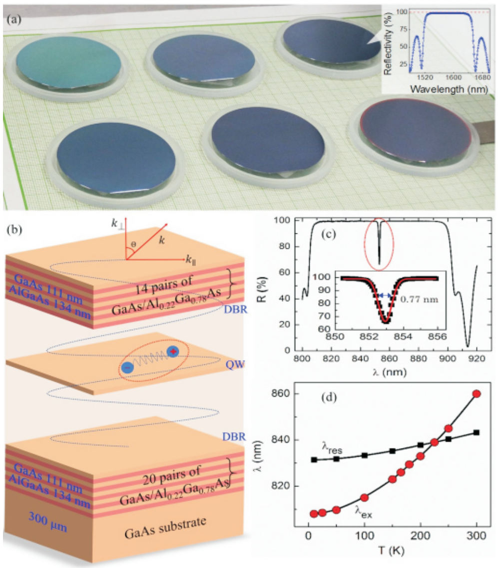

Fig. L.4.1: (a) Photograph of six DBR mirrors, where the inset shows the reflectivity spectrum of 1550 nm DBR mirror, (b) a schematic layer diagram of DBR based cavity resonator with polariton structures, (c) reflectivity spectrum of high Q resonator cavity structure, inset shows the width of resonator cavity, and (d) temperature dependence of excitonic transition (λ_{ex}) along with that of the cavity resonance (λ_{res}).

The developed mirrors are being tested for the measurement of thermal noise for the possible applications in Laser Interferometer Gravitational-Wave Observatory (LIGO). Additionally, the resonator cavity structures are also being used for estimating the unique parameters of polariton structures for developing advanced opto-electronic devices.

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